

BEAMED AND UNBEAMED X-RAY EMISSION IN FR I RADIO GALAXIES

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Work during this period concentrated on a systematic application of the same analysis techniques to all the Fanaroff and Riley Type 1 (FR1) radio galaxies in this program. The sample of FR1 radio galaxies selected from the B2 radio survey and for which ROSAT PSPC and/or HRI observations have been or will shortly be made now numbers 22 objects (17 from our proposals), including the targets from our successful proposal submitted during the reporting period in response to ROSAT AO6.

Software developed by Steve Snowden (GSFC) for background and exposure corrections was installed and run on the data-sets for the eight sources with PSPC exposures. Radio maps were superimposed on the ROSAT images of several of the radio galaxies. The X-ray contours were overlayed on the digitized Palomar Optical Sky Survey images available from STScI, using the SkyView program from GSFC. Results from the X-ray spectral and spatial analyses, and the relationships to the radio and optical properties, are being tabulated and written up for a journal paper, and publication-quality figures have been produced.

A major finding from our work is that FR1 radio galaxies are complex and diverse X-ray emitters. The fraction of compact versus extended X-ray emission varies widely between objects. Simple conclusions from pre-ROSAT correlations (e.g., an X-ray versus core radio luminosity correlation as pointing to a non-thermal origin for all the X-rays) are not to be trusted. Some radio structures appear to be overpressured with respect to their X-ray environments, whereas others may be in pressure contact and shaped by the

external medium.

Results of the work were presented at several forums. First, a poster paper of results was presented at the New England Regional Quasar and AGN meeting, Boston University, May 17th 1995. Second, D. Worrall's colloquium presented to the SAO Summer Interns (undergraduate students) in July 1995 drew largely on work from this program. Third, results from the program were the focus of M. Birkinshaw's talk at the conference 'Energy Transport in Radio galaxies and Quasars', Tuscaloosa, September 19th-23rd 1995 and D. Worrall's talk at the conference 'X-radiation from the Universe', Wuerzburg, Germany, September 25th-29th 1995. A preprint containing these two conference papers is attached to this report. Fourth, results from the project were central to D. Worrall's public lecture at the CfA Monthly Observatory Open Night in October 1995.

A successful ASCA proposal was written in September 1995 for high resolution spectroscopy of two sources to complement the ROSAT results.

In related work, a collaborative paper with C. O'Dea of STScI was submitted to the *Astronomical Journal* in June 1995 and it appeared in the January 1996 issue. The work used techniques developed for this program to search for clusters around three radio galaxies selected for their particular radio morphology.

ROSAT Results for Radio Galaxies

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Abstract. Simple conclusions concerning the origin of X-ray emission in radio galaxies from pre-ROSAT correlations (e.g., X-ray versus core-radio luminosity) are not to be trusted. Radio galaxies are complex and diverse X-ray emitters. Current answers to key questions are presented.

1. Introduction

When ROSAT was launched, the dominant X-ray emission mechanism in radio galaxies as a class was unclear, with detailed study of only a few objects possible. Although statistical tests were applied to samples, conclusions were ambiguous, with correlations between X-ray and radio emissions used to argue either a nuclear origin (e.g., Fabbiano et al. 1984) or a thermal origin (e.g., Feigelson & Berg 1983) for the X-rays. Thus, questions for ROSAT include:

1. Are the X-rays nuclear, thermal, or a combination?
2. What constraints are placed on relativistic beaming models which unify BL Lac objects and Fanaroff and Riley type 1 (FR1) radio galaxies through orientation?
3. Is there sufficient external pressure to give static support to the radio jets and lobes?
4. If hot gaseous atmospheres are seen, are they shaped by the radio jets or is the converse true?

To attempt answers, we have used ROSAT pointings to study a complete sample of FR1 galaxies and additional galaxies with particularly prominent large-scale radio jets. The sample is a complete subset of the 2nd Bologna radio-galaxy sample matched to BL Lac objects in isotropic emission (Ulrich 1989); the sources display a distribution of radio core prominence and radio structure size (which the relativistic-beaming framework interprets as a variation in orientation angle).

2. Results

Our straightforward approach to Ques. 1 is to extract from the ROSAT images radial profiles centered on the galaxies. We have fitted these profiles with convolutions of the point response function (PRF) with β -model and unresolved components. It became evident from our first PSPC fields

that the galaxies required a combination of unresolved and resolved emission, but that the range of relative brightnesses between these components was far from constant (Birkinshaw & Worrall 1993; Worrall & Birkinshaw 1994, 1995; Worrall, Birkinshaw, & Cameron 1995). Simple conclusions concerning the origin of the X-ray emission from pre-ROSAT correlations (e.g., X-ray versus core-radio luminosity) are not to be trusted. Radio galaxies are complex and diverse X-ray emitters.

The complexity and diversity is illustrated in Figure 1, which shows PSPC images of four galaxies with radio contours superimposed. Two of the fields, NGC 315 and NGC 6251, are dominated by small-scale X-ray emission. In the case of NGC 315 we are able to identify at least half of this central X-ray emission with hot gas (Worrall & Birkinshaw 1994), although the size (galaxy scale) is small compared with the radio jet whose northwest extension is several times larger than shown. The resolved X-ray emission in NGC 6251 is only about 7% of the total and, although the unresolved component is sufficiently bright for X-ray spectroscopy, results are ambiguous, allowing either an absorbed component or an unabsorbed hard power law mixed with sub-galaxy scale gas (Birkinshaw & Worrall 1993).

The other two fields in Figure 1, NGC 326 and NGC 4261, show relatively stronger and more complex gaseous environments. NGC 326 is dominated by asymmetric X-ray emitting gas of cluster dimension; it has an extremely weak unresolved component (Worrall et al. 1995). In NGC 4261, while components of gas of galaxy and group dimensions are measured (Worrall & Birkinshaw 1994; Davis et al. 1995), there remains a relatively bright component which is unresolved to the PSPC.

The diversity of the X-ray structures provides a corresponding diversity of answers to Ques. 3 & 4. Jets such as NGC 315 and NGC 6251 appear to be overpressured with respect to their X-ray environments (Birkinshaw & Worrall 1993, 1995). Jets such as NGC 326 and NGC 4261 may be in pressure contact and shaped by the external medium (Worrall et al. 1994, Birkinshaw & Worrall 1995).

The complexity, diversity, and difficulty in determining the nonthermal or thermal nature of unresolved emission complicates the investigation of Ques. 2 despite the growing size of the sample for which ROSAT data are in hand. Better spatial resolution is offered by the ROSAT

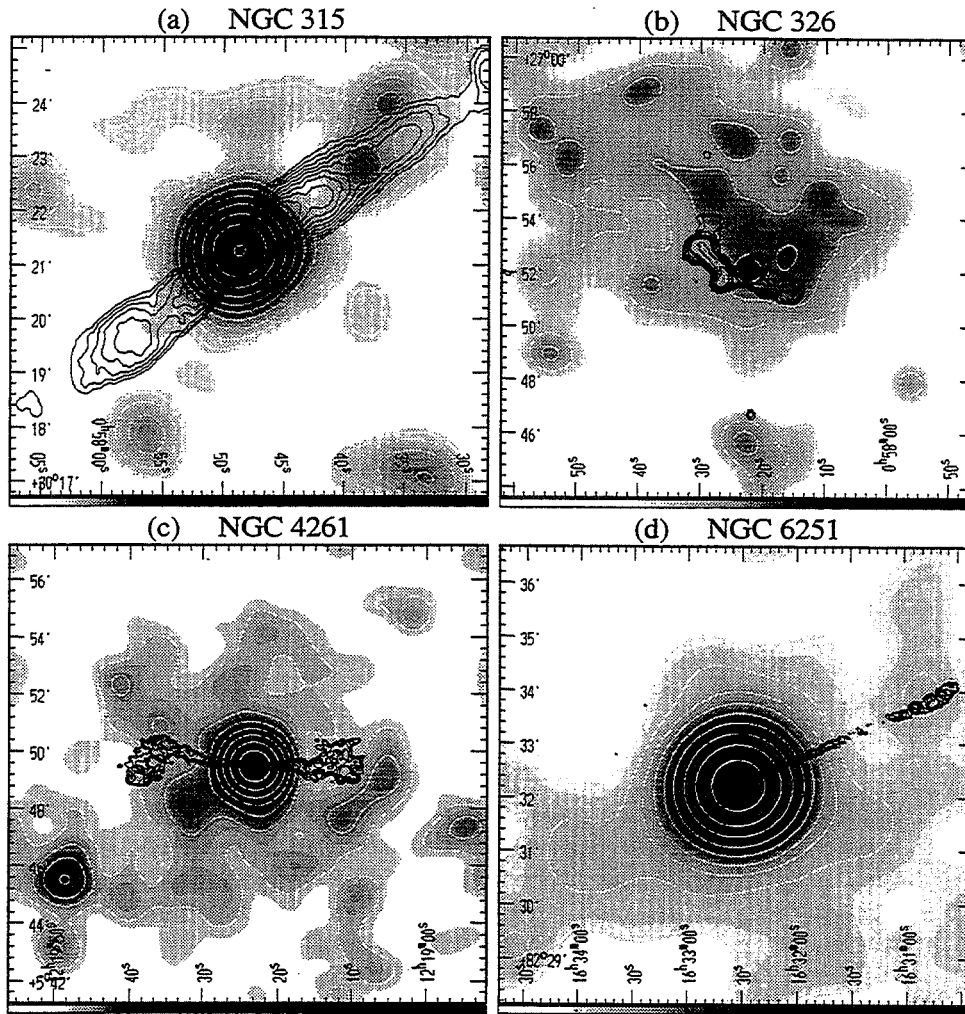


Fig. 1. Radio maps (black contours) of four galaxies superimposed on ROSAT PSPC X-ray emission (greyscale images and white contours). Coordinate grids are J2000. Note that NGC 315 and NGC 6251 have different scales from NGC 326 and NGC 4261. Radio data: (a) NGC 315. DRAO Seven-antenna Synthesis Telescope, 1.4 GHz (Willis & O'Dea 1995, private communication). (b) NGC 326. VLA C-array, 1.4 GHz (Parma, Cameron & de Ruiter 1991). (c) NGC 4261. VLA C-array, 5 GHz (Birkinshaw & Davies 1985). (d) NGC 6251. VLA A-array 330 MHz (Birkinshaw et al. 1995).

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HRI, although improvement over the PSPC is degraded by the wings of the PRF and uncertainties in satellite aspect. ASCA offers improved spectral resolution, but the sources are sufficiently weak to make separation of components difficult without better spatial resolution. ROSAT data now being analyzed will provide further progress in answering the questions posed, and the X-ray study of radio galaxies will be a fertile field for the upcoming generation of observatories.

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X-ray Properties of Radio Jets

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Abstract. ROSAT observations of the atmospheres of a number of radio galaxies containing prominent jets are described. The imaging and spectroscopic results obtained by the PSPC are used to obtain fluxes for the non-thermal core sources and structures for the atmospheres of the host galaxies or their groups. The implications for the environments of the radio jets and for the radio cores are discussed.

1. Introduction

Some well-known radio galaxies are associated with equally well-known X-ray sources. The example that comes first to mind is probably M87. In this case the X-ray emission has three components — associated with the core of the galaxy, with the jet, and with the atmosphere (Biretta, Stern & Harris 1991 and references therein). The first two of these components are directly associated with radio (and optical) structures. Thermal emission from the atmosphere of the galaxy does not have a direct radio counterpart, but may affect the structure and evolution of the radio source through its gas-dynamical interactions with the jet and the halo plasma (e.g., Böhringer et al. 1993).

This degree of X-ray detail was available for few objects until the launch of ROSAT. Instead, the *Einstein* X-ray detections of radio galaxies were used in statistical tests to examine whether the X-rays were associated mostly with the non-thermal core of the radio galaxy (as concluded by Fabbiano et al. 1984) or with the thermal atmosphere (Feigelson & Berg 1983). Where a thermal interpretation was adopted (e.g., Feretti et al. 1990), inferences could be drawn about the environments of the radio sources and used to study the interaction between the jets and the ambient medium (e.g., Miller et al. 1985).

We have used the higher resolution and sensitivity of ROSAT to study individual radio galaxies with prominent, large-scale, radio jets and a well-defined complete sample of low-power objects. In order to get the cleanest diagnostics of the X-ray emission, we have concentrated on relatively isolated radio galaxies — where the confusing effects of cluster gas are minimised. The detailed questions that we are attempting to address are

- Are the X-rays produced by an active galactic nucleus (AGN) associated with the radio core, by a galaxy atmosphere, or by a combination?

- What does the presence (or absence) of X-ray emission from an atmosphere imply about pressure confinement of the radio jets and lobes?
- If an atmosphere is seen in the X-ray, then are structural features in the atmosphere and the radio source related?

In the present paper, we will concentrate on four well-known radio galaxies, NGC 315 (Bridle et al. 1979), NGC 326 (Ekers et al. 1978), NGC 4261 (Birkinshaw & Davies 1985), and NGC 6251 (Perley, Bridle & Willis 1984), and relate their X-ray structures to the issues listed above.

2. ROSAT PSPC data

Each of the four radio galaxies was observed in soft X-rays with the ROSAT Position Sensitive Proportional Counter (PSPC; Pfeiffermann et al. 1986) in ‘wobble’ mode to spread out the effect of the window-support mesh. The data were processed by the Standard Analysis Software System (Gruber 1992), and then further analysed by the Post Reduction Off-line Software (Worrall et al. 1992). Radial profile fitting was performed using convolutions of the energy-dependent point response function (PRF) of the PSPC with β -model and other components (as in Worrall & Birkinshaw 1994).

The general properties of the four galaxies are described in Table 1, and broad-band X-ray images of NGC 326 and NGC 6251 are shown in Figure 1. These images illustrate the general rule, that the galaxies are associated with a source with smaller angular size than the PSPC’s FWHM (about 25 arcsec), superimposed on an extended component. The range of relative brightnesses of the core and extended components is large: for NGC 6251 most of the X-ray flux lies in the core, for NGC 326, almost all of the flux lies in the asymmetric, cluster-scale, halo.

Table 1. Summary of galaxy data

NGC	Redshift	$\log N_{\text{H, gal}}/\text{cm}^{-2}$	$\theta_{\text{cx}}/\text{arcsec}$	$L_{\text{u}}/10^{34} \text{ W}$	$L_{\text{r}}/10^{34} \text{ W}$
315	0.0165	20.76	13	7	4
326	0.047	20.74	230	4	280
4261	0.0073	20.20	21	1	1
6251	0.024	20.74	130	30	8

^a L_{u} and L_{r} are the 0.2 – 1.9 keV luminosities of the unresolved and resolved components of the sources as implied from a spectral separation of components (see Worrall & Birkinshaw 1994 and Worrall, Birkinshaw & Cameron 1995 for details).

^bThe core radius, θ_{cx} refers to a β -model with $\beta = 0.67$. For NGC 326 the core radius is for the SW section, where the gas is least extended.

^c $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is used throughout the paper.

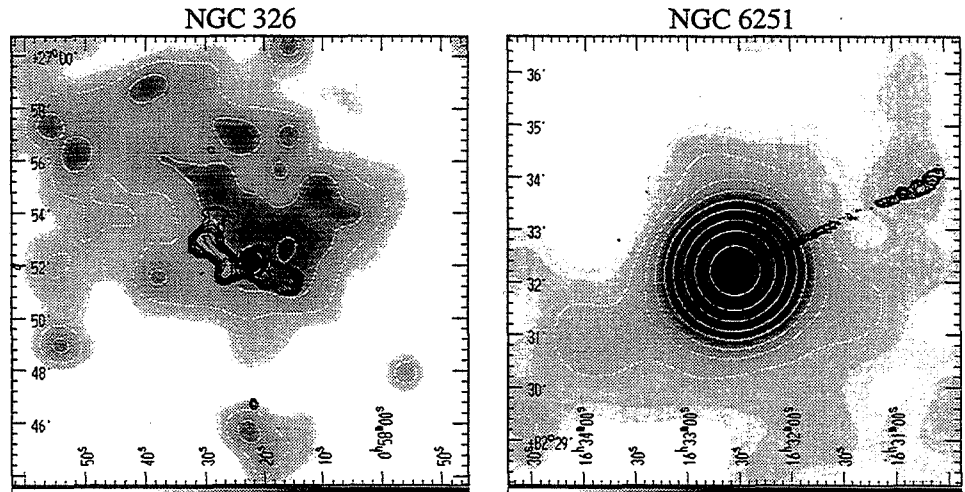


Figure 1. NGC 326 (left) and NGC 6251 (right) shown in ROSAT PSPC broad-band X-ray images and white contours, with 1.4 GHz (NGC 326) and 330 MHz (NGC 6251) radio contours superimposed in black. NGC 326 shows obvious asymmetric X-ray emission and a weak core. NGC 6251 shows a bright X-ray core and faint extended emission. Note the different scales of the two images.

3. Four Galaxies

3.1. NGC 315

The X-ray emission of NGC 315 (Worrall & Birkinshaw 1994; Birkinshaw & Worrall 1994b, 1995) is dominated by an unresolved component making up about 60 per cent of the X-ray counts. This is surrounded by a component with core radius ≈ 8 kpc and $k_B T_e \approx 0.5$ keV.

Exceptionally, the source shows bright, localised, emission from two regions close to the radio jet, with the more southerly of these components lying on the centerline of the jet. However if this component is related to the radio jet, then it differs from the X-ray emission in M 87 by lying just beyond a major radio brightening, rather than in the brightest radio knots. Nevertheless, there is a radio feature at the same location and an association is possible.

The extended X-ray emission near NGC 315 corresponds to gas which is underpressured relative to the minimum energy pressure in the radio jet. The scale of the atmosphere is also smaller than the scale of the jet, so that the pressure imbalance becomes larger at increasing distances from the center of the source. The small linear scale of the extended X-ray emission implies that the atmosphere is likely to be participating in a central cooling flow.

3.2. NGC 326

The X-ray image of NGC 326 (Fig. 1; Worrall et al. 1995) is dominated by an asymmetrical extended component that lies mostly to the NE of the radio source. Although a small angular-scale component can be distinguished on the image it provides only a small fraction of the overall X-ray counts. Clearly this

is not an ‘isolated’ galaxy, but rather a galaxy in the edge of a significant cluster atmosphere (associated with the western part of Zw 0056.9+2636). Thermal emission at $k_B T_e \approx 2$ keV can be traced on scales > 1 Mpc, while the point source is too weak for a useful spectral analysis to be possible.

The high pressure in the thermal gas near NGC 326 makes static pressure confinement of the radio emission possible in the outer, lower-surface brightness, parts of the source. Here the strongly distorted structure of the source, which has been attributed to jet precession (e.g., Ekers et al. 1978) or motions of the two component galaxies of the dumbbell system (Wirth, Smarr & Gallagher 1982), can instead be interpreted in terms of buoyancy forces (Worrall et al. 1995), provided that the lobe densities are low (a few percent of the density in the ambient medium) and trace a buoyant backflow.

3.3. NGC 4261

About half the X-ray counts from NGC 4261 originate in a component with scale < 1 kpc, while the remainder lie in a galactic halo (with scale ≈ 4 kpc; Worrall & Birkinshaw 1994) and a group component (with scale ≈ 25 kpc; Davis et al. 1995). Spectral fits are consistent with the interpretation of these structures as a mini-AGN (with a hard spectrum), a galactic halo (with $k_B T_e \approx 0.6$ keV), and the atmosphere of a massive group (with $k_B T_e \approx 1$ keV).

A comparison of the minimum energy pressure in the radio jets and lobes and the thermal pressure from the atmosphere (Birkinshaw & Worrall 1994b, 1995) shows that the source can be confined by static pressure over the entire jet region, with pressure equality being reached at the lobes (~ 30 kpc from the core). Furthermore, the density of the galactic gas is such that it is likely to be participating in a strong cooling flow.

No excess, or clear reduction, of the X-ray emission is seen from the regions of the radio jets or lobes.

3.4. NGC 6251

The X-ray image of NGC 6251 is heavily dominated by a pointlike component (Fig. 1), although detailed radial fitting reveals that about 7 per cent of the X-ray counts lie in a component with a scale ≈ 90 kpc (Birkinshaw & Worrall 1993). The spectrum of the core cannot be fitted by a single component absorbed only by the Galactic column of neutral gas.

The extended, thermal, X-ray emitting gas cannot provide sufficient static pressure to balance the minimum energy pressure of electrons and magnetic fields in the radio jet, and dynamical effects are a plausible source of the missing confining pressure (Birkinshaw & Worrall 1993). The detailed interpretation of the core X-ray spectrum suggested the presence of either a hard power-law component, or a large absorbing gas column at NGC 6251. Searches for this absorbing column with the VLA (Birkinshaw & Worrall 1994a) suggest that it may be present.

It is worth noting that the radio jet is not associated with any detectable X-ray emission, although such emission would have been detected if the X-ray/radio ratio resembled that of M 87’s jet.

4. Conclusions and Future Work

In general these radio sources contain a small-scale component and larger-scale components associated with one or more of the galaxy, group, or cluster atmospheres. The core is sometimes dominant (e.g., NGC 6251), but may be very weak (e.g., NGC 326). This diversity implies that statistical results based on a single canonical structure for X-ray emission from a radio galaxy are unlikely to be useful. Other lessons that we draw from these data are

- The core X-ray emission may be produced by local hot gas (in a cooling flow) or a mini-AGN, but better spatial and spectral resolution are needed to study this. ROSAT HRI data are in hand, but their spatial improvement over the PSPC is degraded by extended wings of the PRF and uncertainties in the aspect of the satellite. ASCA spectra help, but the X-ray sources are weak, and spatial separation of the spectral components is difficult. The resolved spectral capabilities of AXAF will contribute enormously to this study.
- The more powerful radio jets are overpressured relative to the static pressure of their atmospheres, although those atmospheres do provide significant static pressure even in the most isolated galaxies. Possibly a dynamic pressure contribution is dominant in these cases. For the weakest jets (e.g., NGC 4261) the external pressure may determine the kpc-scale structure of the source.
- Jet X-ray emission is usually weaker than would be predicted from an extrapolation of the radio to X-ray ratio in M 87, indicating the exceptional nature of M 87's jet.

Much further work of this type remains to be done on these galaxies and samples of radio galaxies (e.g., Worrall & Birkinshaw 1995), and the observational tools for performing that work will be coming available in the next few years.

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